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Food security and climate change: the case of rainfed maize production in Mexico

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ABSTRACT

Climate change has altered global rainfall amounts and seasonality. Rainfed crops are particularly dependent on foreseeable rainfall, thus yields of maize, wheat and sorghum have decreased globally. Rainfed maize is the cornerstone of the agriculture in Mexico and the nutrition base of as many as twenty million people. Despite its relevance, the risk that climate change represents for this economic activity has not been studied in our country. We evaluated the link between rainfall variability and maize yields in Mexico across three different time periods: the present, the past 30 years and the remainder of this century (future) with RCPs scenarios. We found that rainfed agriculture was distributed as a function of the dry-season length, occurring in areas with a 4–9 months dry season, thus climate change may alter not only agricultural yields, but also the spatial distribution of land uses. There was a linear correlation (r = 0.45) between mean annual precipitation and rainfed maize production nationally for the period 1980–2012. The correlation was stronger (r = 0.91) during 2005–2012 when high-resolution data were available for the analysis. Correlation values were not homogeneously distributed within the country, although the minimum correlation was 0.35. In the future scenarios, yields were predicted to either not change or to decrease by as much as 10%. The strongest negative impacts were predicted across the Northeast and the South of the country, where yields declined by up to 30% in all scenarios.

1. Introduction

One consequence of climate change is the alteration of global hydrological patterns (Allan and Soden, 2008) with large-scale changes in rainfall amounts (e.g. Chou et al., 2013; Donat et al., 2016), in river discharges (Gedney et al., 2006; Piao et al., 2007), drought frequency (Dai, 2013) and intensity (Trenberth et al., 2014) and changes in dry-season length (Murray-Tortarolo et al., 2016a; Murray-Tortarolo et al., 2017). These hydrological alterations have made water availability less predictable in terms of amounts and seasonality, a pattern likely to strengthen into the future (Collins et al., 2013).

Agriculture, particularly rainfed, is highly dependent on foreseeable rainfall and runoff patterns. Climate change, mainly the alterations of the hydrological cycle, represents a threat to food production and security (Nelson et al., 2014). A world in which rainfall is less predictable, in time and amount, implies a greater challenge to fulfill crop needs for water, which in turn leads to lower yields and higher food prices (Schmidhuber and Tubiello, 2007). Consequently, food production systems need to maintain their productivity and cope with hydraulic shocks and long-term stress (Gregory et al., 2005). Such a task needs to be dealt with regionally, as the risk of the food production systems to climate change is not uniformly distributed across the planet (Porter et al., 2014).

Reduced food production as a consequence of climate change has already been reported. In the case of wheat, Asseng et al. (2013) found that yields were reduced by 5% $^{\circ}C^{-1}$ when temperatures raised above 32 °C. Fischer et al. (2005) used several global circulation models to assess the impacts of changing climate on global cereal production and found an increase in the yields across Europe, Canada and Russia, but a strong decrease elsewhere, particularly USA, Brazil and Australia. Maize production was also found to decrease at least 10% in Latin America and Africa under several scenarios by 2055 (Jones and Thornton, 2003). Globally, climate change impacts are predicted to be negative for the major crops, with decreasing global yields up to -2% per decade (Porter et al., 2014).

Maize represents the cornerstone of agriculture in Mexico. It is grown in 35% of the cropland area of the country and 59% of the rainfed agriculture area (SIAP, 2017). At least half of the total area is used to grow self-consumption maize, thus, it represents the nutrition base for at least 20 million people, particularly in low-income regions

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usually inhabited by indigenous people (Challenger, 1998). Traditionally, maize is grown along with other crops, commonly beans, squash and/or chilies, as an integrated multi-story production system (milpa) that seeks to harvest as much water and energy as possible. The milpa production system developed for over 8000 years, leading to the evolution of at least 42 different maize varieties adapted to local conditions (Corral et al., 2008). Consequently, maize production in Mexico is usually rainfed and highly dependent on seasonal precipitation, such that yields are strongly correlated to rainfall rates at the national level (Challenger, 1998), a relationship that has existed for at least the last 500 years (Therrell et al., 2006). The social, economic and climatic particularities of this production system create a direct link among rainfall, production, food security and human welfare, thus leading to a high social risk to climate change.

The sensitivity of maize agroecosystems to rainfall variability can be seen in years of contrasting precipitation. Low precipitation in Mexico during 1997–1998 led to a 25% decrease in the total production of maize (Challenger, 1998). In contrast, record maize production was documented during the humid 1991–1993 period (Challenger, 1998). Worrisome, most IPCC future scenarios for the country predict a decrease in precipitation and an increase in temperature (Murray-Tortarolo et al., 2016b), which are likely to lead to longer and more intense droughts. Yet, their potential impact on maize production at the national level and regionally within the country has not been investigated.

In this study, we assess the risk of rainfed maize production in Mexico to climate change, as an example of a relationship between climate, food security and human welfare. In doing so, we address the following questions:

1 Present: how are rainfall and rainfed agriculture linked at the whole country level?
2 Past: what has the relationship between changes in rainfall and changes in maize yields been through time and regionally in Mexico?
3 Future: what changes could we expect in rainfed maize yields under future climate scenarios?

2. Methods

2.1. Datasets

We used global climatic observed datasets to obtain national precipitation and temperature for the past century (1901-2013) (CRU3.2-Harris et al., 2014), national governmental data for land use types (CONABIO, 2017), maize production in Mexico for the last 50 years (Sagarpa, 2017 and SIAP, 2017), gridded maize yields for the period 2005–2012 (SIAP, 2017), and modeled climatic data from CMIP5 models for the future scenarios (Taylor et al., 2011) (Supplementary 1). All datasets were interpolated and/or re-gridded to a 0.1 × 0.1° grid to match scales for the analyses. All datasets are freely available online and post-process data is available under request.

2.2. Data analysis

For the present time analysis, the mean dry-season length was calculated based on the number of consecutive months of a given year that had less than 100 mm of precipitation (Murray-Tortarolo et al. 2017). We used the mean dry-season length (DSL) across all years for each grid (1901-2009) (Fig. 1-b) and national maps for land use, soils and vegetation types from CONABIO (1998) which grouped the territory into 54 different categories. From those, irrigated agriculture, rainfed agriculture and induced grasslands were chosen to represent human-managed areas (Fig. 1-c). It is important to note that pixels where at least 50% of the land cover corresponded to one of these activities were assigned to the corresponding land use, otherwise they would be assigned to the dominant vegetation or land use in the pixel, which was represented as “other” in the resulting map. The area of each activity was grouped as the sum of pixels per mean dry-season length. Thus, we were able to construct curves of the three land use types based on the dry season length (Fig. 1-d).

For the analysis on past trends, national data from SAGARPA (2017) for maize production (1980-2005) and high-resolution national gridded data (2005-2012) from SIAP (2017) were used. As maize yields increased over time in the long-time series, we detrended the production by time and calculated the yearly anomaly. The same procedure was employed for precipitation and the rainfall anomaly was plotted against the maize production anomaly (Fig. 2a). In addition, we plotted the gridded mean national maize production against the mean precipitation for years with high-resolution maize data (2005-2012) (Fig. 2b) and the gridded correlation between the two variables for the same time period (Fig. 3).

For the analysis on the future scenarios, we used the mean gridded precipitation data for the period 2090–2099 minus the mean gridded observed data for 2000-2009. This allowed accounting for the net change in precipitation by the end of the next century for each pixel. We attempted to replicate this procedure with temperature data, but we found no strong historical (temporal or spatial) correlation with maize production or yields (Supplementary 2); hence, the resulting map showed no future risk.

To obtain a simple model of the possible changes in maize yields by 2100, the changes in precipitation were multiplied by the ratio of maize yield divided by the mean observed precipitation for each grid, as described in Eq. (1).

$$\Delta Yields_{2100} = \left(\frac{Yields_{2000}}{Precipitation_{2000}}\right)^{*} \Delta Precipitation_{2100} \quad (1)$$

This procedure was applied in 14 models for 4 RCPs (RCPs 2.6, 4.5, 6.0 and 8.5; 56 combinations, Supplementary 1), but only the results for the model ensemble are shown, both gridded and by country mean (Table 1).

To construct a map of the risk to climate change the following two parameters were used: 1) the gridded likelihood of precipitation decreasing by 2100 and 2) the gridded level of dependency between production and rainfall. The likelihood of decreasing precipitation was calculated based on all four RCPs as the number of cases in which precipitation declines by 2100. For example, a region with 50% likelihood means that precipitation decreases in two RCPs. The level of dependency is the correlation of maize production and rainfall as shown in Fig. 3. The resulting map highlights areas with a different likelihood of a decrease in maize production despite the future scenarios considered.

3. Results

Mean annual precipitation (MAP) in Mexico during the last century followed a distinctive spatial pattern. There was high rainfall in the south (~2000 mm/year) and less over the north (~100 mm/year), and significant precipitation in both the east and west due to the presence of high mountainous ranges (Fig. 1a). The rainfall amounts were linked to the seasonal distribution of water, with shorter dry seasons (DS) occurring in areas with higher MAP (Fig. 1b). Interestingly, 71% of the country showed DS of at least 6 months and 42% of more than 8 months, which means that most of the country’s precipitation falls into a single well-constrained rainy season.

Among the three types of land use examined, we found that the country’s dominant production activity in terms of area was rainfed agriculture. This activity occurred in areas with 4–9 months dry seasons and occupied 35% of the arable land of the country. Other economic activities were also distributed as a function of water availability, but occupied comparatively less area. For example, the main areas of

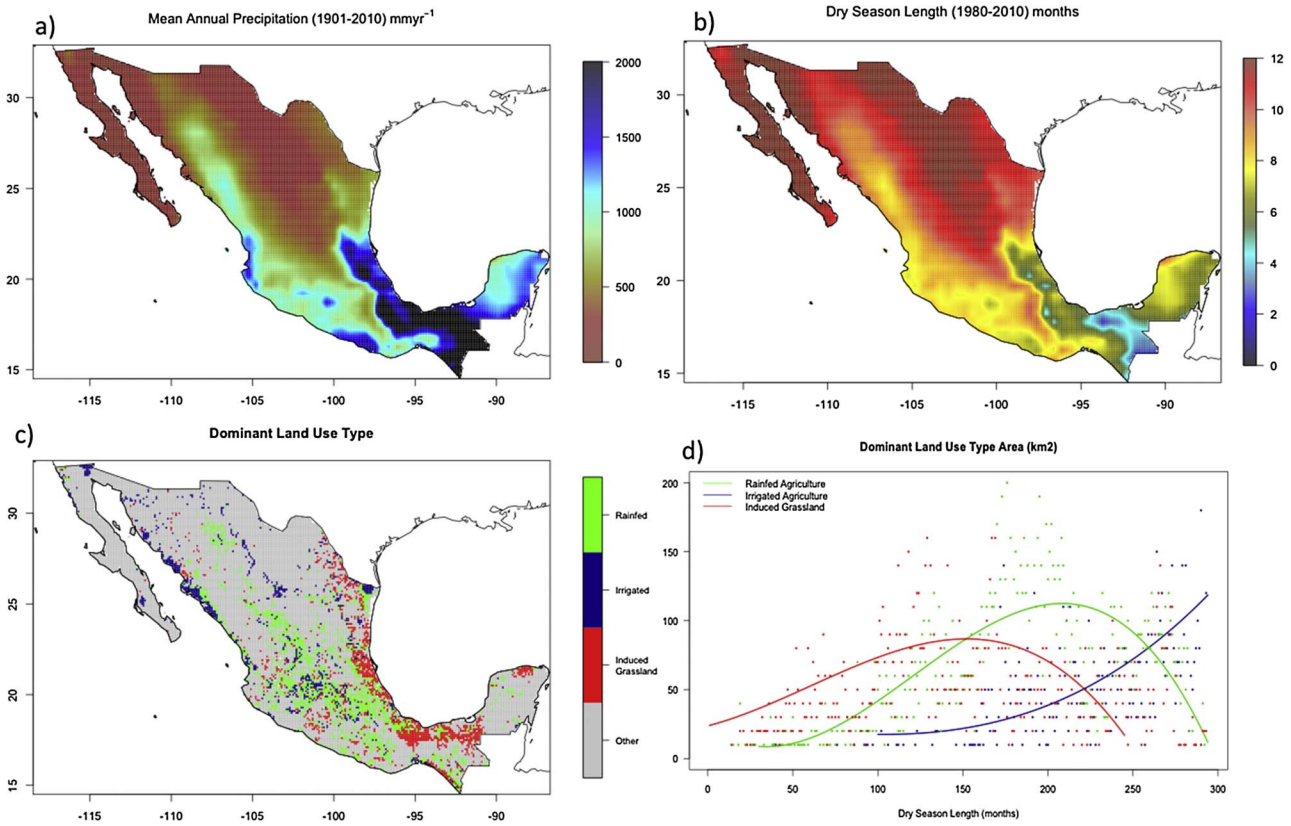

Fig. 1. Current distribution patterns of rainfall amounts (a) and seasonality (b), dominant land use types (c), and land use type distribution as a function of dry-season length (d) (For interpretation of the references to colour in the text, the reader is referred to the web version of this article).

induced grasslands were located over the wettest regions along the East coast and small patches of rainfed agriculture occurred near rivers, mostly in the north (Fig. 1c).

When the type of land use was grouped according to the length of the dry season a clear separation between the activities was found. Induced grasslands, used as pastures for cattle, occurred in areas with large amounts of MAP and short dry seasons (less than 3 months) (Fig. 1d, red line). In areas with an extended DS (4–9 months), the dominant economic activity was rainfed agriculture (Fig. 1d, green line). Regions with less than 3–4 months of rain were used for cultivation through irrigation (Fig. 1d, blue line).

We tested the relationship between climate and rainfed agriculture production, using rainfed maize yields as a case study. The correlation between the anomaly in precipitation and the anomaly in the total rainfed maize production at the national level during 1980–2012 was r = 0.45 (Fig. 2a). The correlation between the variables was stronger (r = 0.91) when data were analyzed for the period 2005-2012, for which municipal level data (high-resolution) was available (Fig. 2b). As would be expected, this relationship was not homogeneously distributed within the country, although all regions displayed a correlation between maize yields and precipitation of at least 0.35 (Fig. 3).

We projected the correlation into the future under four different representative concentration pathways (RCPs; Table 1). The mean precipitation across the country was projected to decrease either slightly (RCPs 2.6, 4.5) or greatly (RCPs 6.0, 8.5). As a result, maize yields and production were predicted to decline nationwide by up to -10% (+1.5 to -10%) by 2100.

The predicted changes did not affect all areas equally. For example, in RCP 2.6 most of the central and Northwest regions of the country (important areas of rainfed maize production) were predicted to have higher precipitation and yields, while the Northeast and the Baja California peninsula would face drier conditions and lower yields (Fig. 4a). Similarly, in RCPs 4.5 and 6.0 we found regions with both increases and decreases in yields, although the dominant trend under both scenarios was negative (both for rainfall and yields) (Fig. 4b and c). Under the most extreme conditions of radiation change (RCP 8.5), precipitation was predicted to decrease nationwide, leading to strong declines in maize yields everywhere, up to 2 Mg ha^{-1} or 80% in some regions (Fig. 4d).

4. Discussion

Our results revealed a distinctive spatial distribution of the land use types at the country level as a result of water availability and dry season length in the present conditions. Globally, the distribution of agricultural practices has been widely mapped as a function of different environmental factors. For example, Ramankutty et al. (2008) used inventory based and satellite derived data, along with climatic fields, to map the distribution of croplands globally for the year 2000. Also, in a recent global approach, Salmon et al. (2015) plotted the distribution of rainfed agriculture, irrigated agriculture and paddy croplands as a function of climate, using remotely sensed and national agricultural inventory data. Nonetheless, to our best knowledge our study shows for the first time the distribution of land uses in Mexico as a result of climatic variation and as a main driver of land use practices. Thus, climate change could result not only in changes in agricultural yields, but also potentially, in a shift of land uses. For example, a continuous decrease in rainfall in a humid area may lead to farmers shifting from pasture to rainfed agriculture.

The analysis on past trends revealed a clear and strong relationship between rainfed maize productivity and rainfall amounts. Similar relationships have been found in other regions where maize is grown under comparable conditions. For example, in Croatia the grain occupies 35% of the arable land and most production is rainfed (Rastija et al., 2012). In 2011, the country faced an 80% reduction in precipitation, which resulted in a decrease of more than 50% in maize

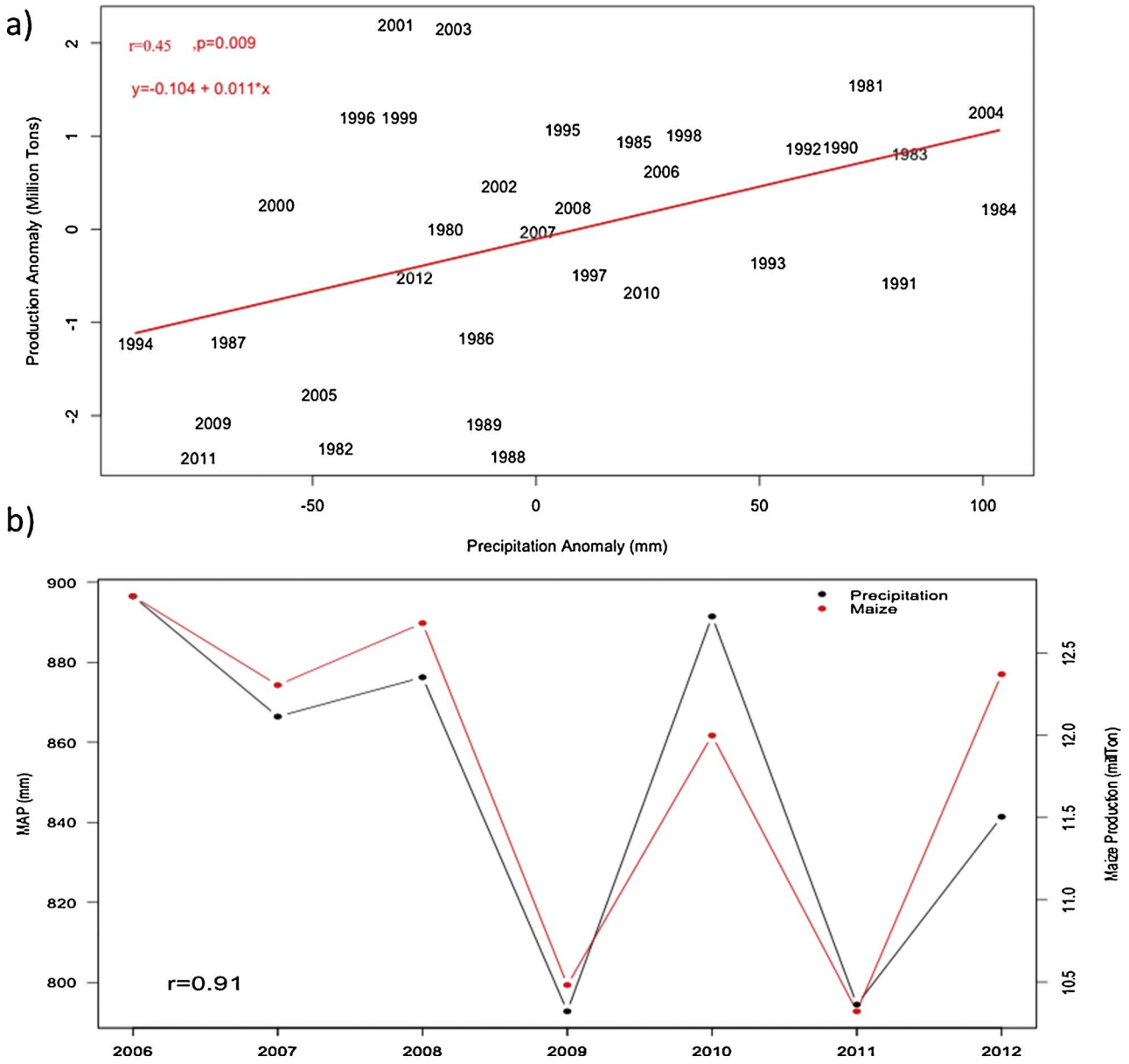

Fig. 2. a) Anomaly in the precipitation vs. anomaly in maize production from 1980 to 2012 for the whole of Mexico. A linear model was fitted and statistics are presented. b) Relationship between mean annual precipitation and maize production in Mexico during 2006-2012 with high-resolution data.

yields. Across the USA, Rosenzweig et al. (2002) found that rainfed maize yields increased linearly with the growing season precipitation during 1951–1998, although extreme precipitation could actually diminish the productivity. Maize yields in Africa were shown to decrease faster under drought conditions when temperature was increased (Lobell et al., 2011). Similar relationships between rainfall and maize yields have been broadly shown in Mexico using national average data (Challenger, 1998), but our study represents the first formal analysis with spatially explicit high-resolution data. Apparently, rainfed maize yields seem to be highly dependent on interannual variability of precipitation, both globally and regionally.

The heterogeneous dependency of rainfed maize yields to precipitation in the country suggests multiple factors may be involved as determinants of maize yields. Firstly, the edaphic conditions, in particular soil type, can affect the ability of maize to tolerate water stress and/or to absorb nutrients, which on its own has been shown to account for up to 19% of the variation in maize yields in the southern USA (Tolk et al., 1999). Secondly, the use and type of fertilizer applied can account for up to 60% differences in yield, although most likely around 10–15% (Ellis et al., 1956). Finally, decisions concerning seeding time (before or during the rainy season) have also been shown to affect yields by up to four-fold in Mexico (Cohen et al., 2014). Thus, local conditions and practices can alter the strength of the dependency between maize yields and precipitation, leading to the spatially-dependent heterogeneous matrix we found. However, in spite of the spatial heterogeneity, all regions show at least a medium dependency on rain. More importantly, the strength of the dependency is not apparently related to mean precipitation, thus, regions with high annual rainfall may be as susceptible to climate change as those across drylands.

We hypothesize that rainfed agriculture is particularly sensitive to climate variability, in contrast to other land uses. For example, cattle production may be buffered from climate variability through the use of grains or fodder obtained elsewhere or may me moved from the site during adverse climatic conditions (Butt, 2010; Butt et al., 2009; Mardero et al., 2015). Similarly, irrigated agriculture does not depend on climate, at least not in the short term, as the main water source comes from inland water bodies (Mendelsohn, 2008). In contrast, the practice of rainfed agriculture does not provide any means of

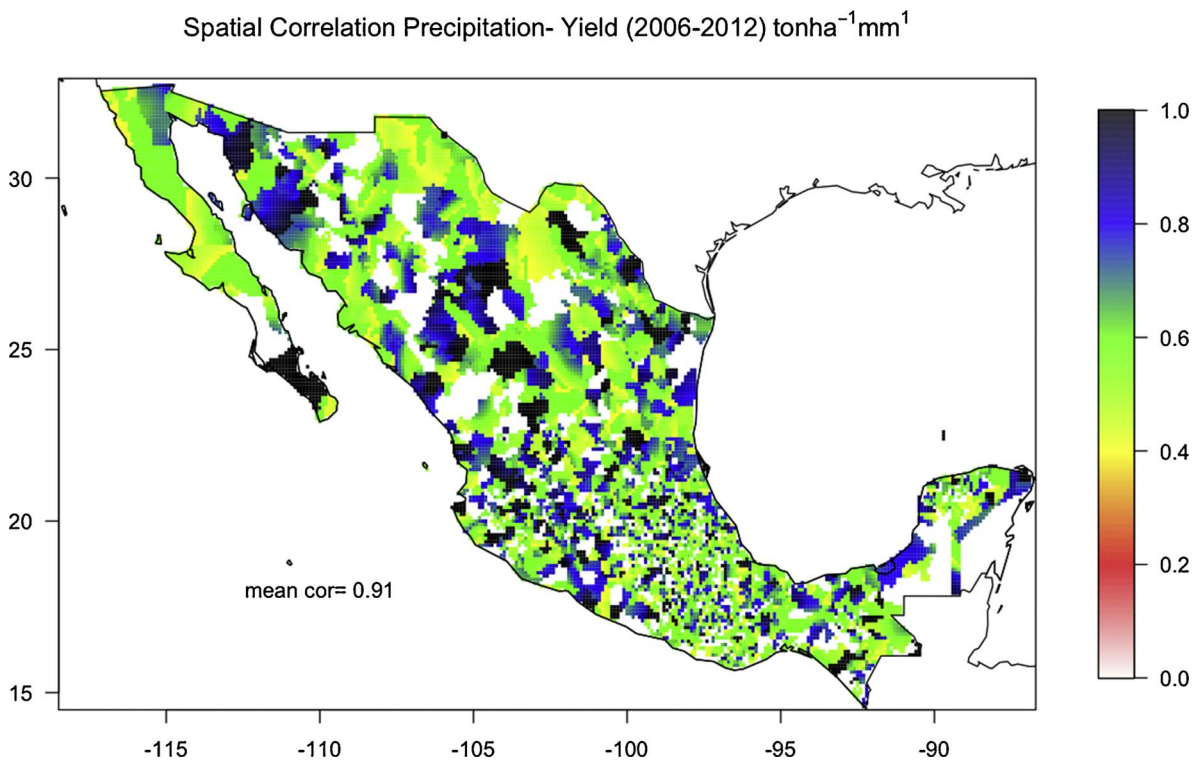

Fig. 3. Spatial correlation between rainfall and maize yields for the years 2006–2012. The total mean correlation is also shown.

Table 1
Changes in precipitation, maize yield and production under the four representative concentration pathways (RCPs) for the remaining of the 21st century in Mexico.

RCP	Mean Precipitation Change (mm)	Mean Maize Yield Change (ton/ha)	Mean Production Change (mill ton and %)
2.6	9.9 ± 15.8	0.02 ± 0.15	+0.05 (0.05%)
4.5	−15.4 ± 21.4	−0.04 ± 0.17	−0.33 (−3.8%)
6.0	−50.3 ± 26.0	−0.13 ± 0.11	−0.89 (−8.4%)
8.5	−97.5 ± 83.9	−0.26 ± 0.21	−1.10 (−10.5%)

adaptation to climate variability, beyond the use of locally adapted maize varieties; hence, dry years lead to decreased yields and vice versa. Given the high number of maize varieties evolved in Mexico, the potential to explore maize response to rainfall variation should prove an interesting avenue for research.

Our future RCPs simulations pointed to a nationwide yield reduction of up to 10%, with regional reductions of up to 80% in RCP 8.5. Similarly, global estimates by Rosenzweig et al. (2014) indicated that maize in Latin America could face a yield decrease between 30 and 50% by 2099 in RCP8.5, using multiple models and observations. Interestingly, their study also showed that such reduction could not be resolved by fertilizer application, since higher N inputs had only a minor effect on diminished yields. It seems very likely that rain will decrease across Mexico in the future and that maize yields will follow accordingly. However, the impacts will not be homogeneously distributed, as the map of maize production risk to climate change suggests (Fig. 5).

It is important to note that our results are based only on precipitation changes, although temperature change could also play a significant role for future maize yields. For example, higher temperatures could lead to stronger evaporative needs or higher vapour pressure deficits, which in turn would result in shorter growing seasons and increased plant mortality due to hydraulic shock. Nonetheless, the lack of historical correlation between temperature and maize yields/production in our study suggests those effects are likely secondary to the predominant regulatory role of precipitation.

Two regions were identified with a high risk of diminishing maize production in response to climate change: the Northeast and the Southeast of the country. The first region may not represent as general a socioeconomic problem since rainfed agriculture is only present in small patches (Fig. 1c) and is not the main economic activity for most of the population (Challenger, 1998). However, the Southeast is mostly populated by low-income indigenous inhabitants, who practice rainfed maize production as a means of subsistence (Challenger, 1998); thus, climate change may have a much stronger socio-economic deleterious effect. Additionally, the region is the centre of origin for maize and several species of the *Zea* genus (wild crop relatives) are distributed in the area (Staller et al., 2016). These wild relatives are traditionally planted with maize to improve yields (Hajjar and Hodgkin, 2007). Thus, the potential to endanger key genetic material is high. It is also important to note that the central region of the country, where most of the rainfed agriculture is concentrated, is apparently at low risk against climate change.

While land practices were clearly aggregated by the local dry-season length in Mexico, it is also important to consider the strong component of human-based decisions affecting land uses. That is, despite the significant proportion of land-use variance explained by rainfall, there is a large proportion of the variation unaccounted for. Thus, our analysis on the past trends and future scenarios should be considered mostly as a biophysical exercise on the potential risks of rainfed agriculture to climate change, when all other conditions remain similar. Our methodology and analysis could be extended to other crops and other regions/countries if adequate data is available, to quickly identify areas where food production may be at risk.

The negative impact of climate was already evident during 2011–2013, when the country faced continuous droughts due to reduced precipitation. During these two years, grain production was reduced considerably and imports grew by 73.9% (ASERCA, 2016). It is clear that adaptation will be needed for rainfed maize production to cope with climate change. This may include the identification and selection of existing drought-resistant maize varieties (Cairns et al., 2013;

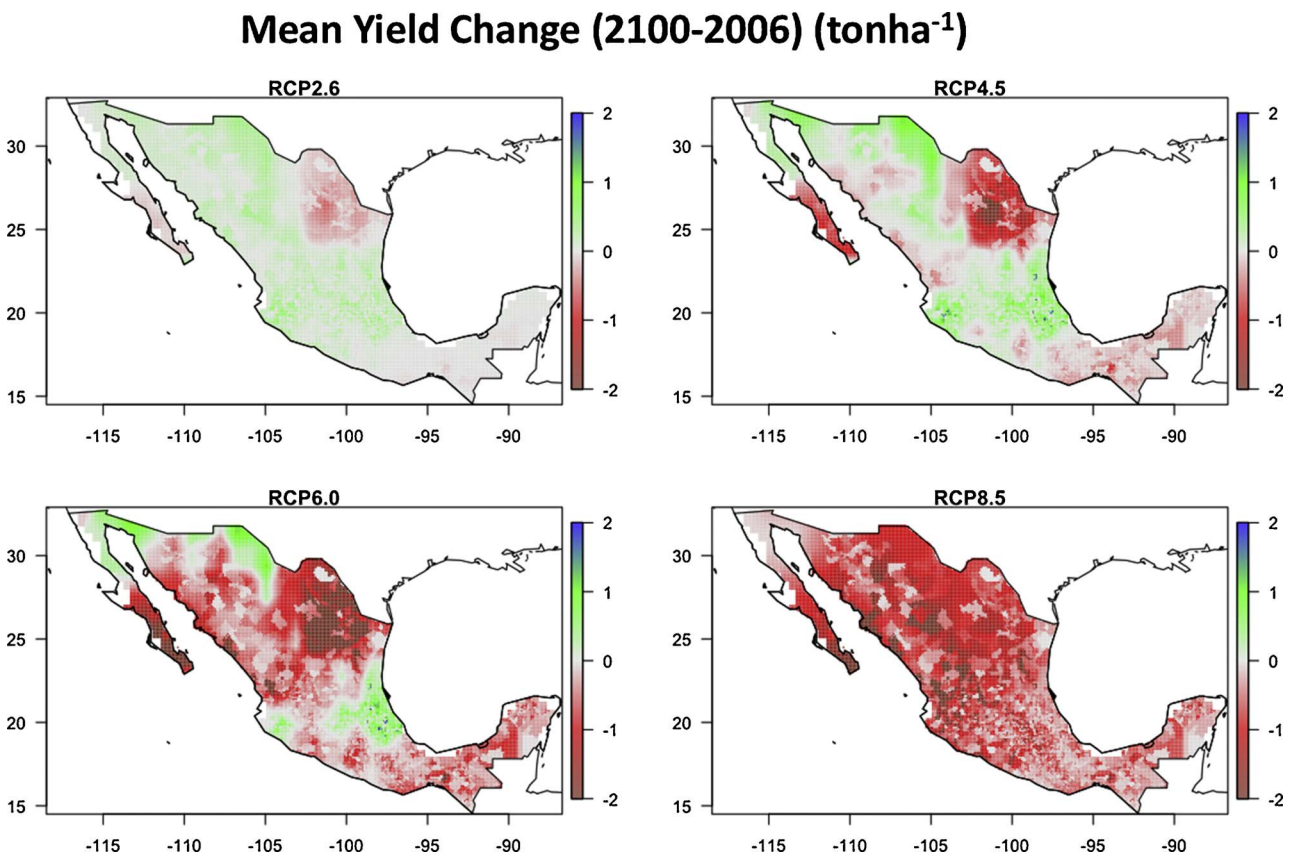

Fig. 4. Maize yield change (ton/ha) in Mexico under four different future RCPs.

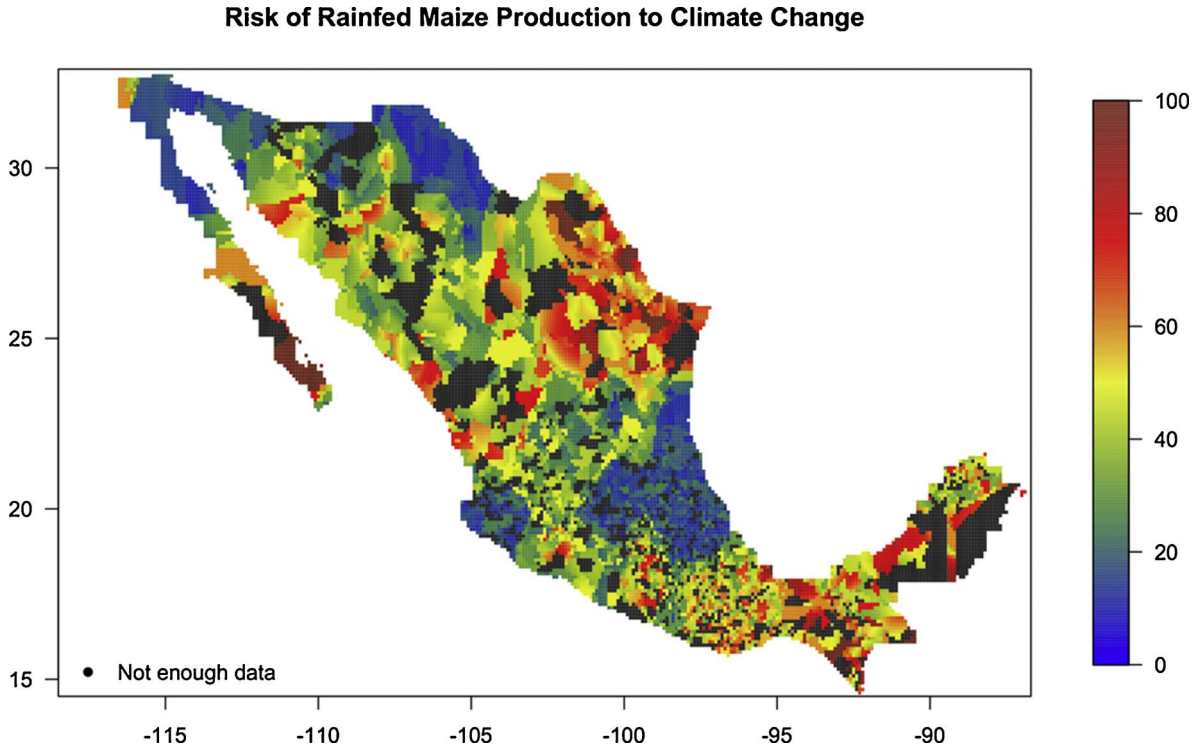

Fig. 5. Risk of maize production to climate change as a probability. A region with 100% chance of being at risk indicates a current strong relationship between rainfall and maize yields, and a decrease in rainfall in all future RCPs.

Lu et al., 2011), the use of genomic estimates for rapid breeding of drought-tolerant varieties (Bänziger et al., 2006), a shift in cultivation practices, particularly the planting time (Sanchez-Cohen et al. 2014), and other strategies that may allow farmers to cope with drought and water-stress.

Author Contribution

The study was designed and executed with equal contributions of all authors. GMT and VJJ wrote the manuscript and JL provided comments for improvement.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.02.011.

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